LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-TR-218053

FY05 LDRD Final ReportThe Innermost Inner Core: Fact or Artifact?LDRD Project Tracking Code 04-FS-019

H. Tkalcic, M. P. Flanagan, H. Mogri

January 10, 2006

Disclaimer

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

FY05 LDRD Final Report
The Innermost Inner Core: Fact or Artifact?
LDRD Project Tracking Code: 04-FS-019
Hrvoje Tkalčić, Principal Investigator

Hrvoje Tkalčić and Megan P. Flanagan

The Atmospheric, Earth and Energy Sciences Department

Lawrence Livermore National Laboratory

Huzefa Mogri

Department of Computer Sciences

University of California, Berkeley

Abstract

P'P' (PKPPKP) are P waves that travel from a hypocenter through the Earth's core, reflect from the free surface and travel back through the core to a recording station on the surface. Here we report the observations of hitherto unobserved near-podal P'P' waves (at epicentral distance < 10º) and very prominent precursors preceding the main energy by as much as 60 s. We interpret these precursors as a back-scattered energy from previously undocumented horizontally connected small-scale heterogeneity in the upper mantle beneath the oceans in a zone between 150 and 220 km depth beneath the Earth's surface. From these observations, we identify a frequency dependence of attenuation quality factor Q in the lithosphere through forward modeling of the observed amplitude spectra of the main and back-scattered P'P' waves. In addition, we did not find that travel times corresponding to very polar paths through the centermost inner core with respect to the rotation axis of Earth are anomalously advanced, which argues for isotropic or at best – weakly-anisotropic center of Earth in the direction parallel with the rotation axis. More systematic sampling near Earth's center and characterization of anisotropy in Earth's center will be a subject of future research efforts.

Introduction/Background

We live in a decade of unprecedented quantity and quality of seismic data, which have accumulated over the years, and are easily accessible online thanks to the IRIS (Incorporated Research Institutions for Seismology) acquisition system. Although the seismological community is growing and the quality of seismic recording is improving constantly, there are still vast amounts of unanalyzed seismic waveforms, which might hold a key to deciphering unresolved geophysical puzzles. A prime example of these puzzles is the current state of understanding the inner core structure. The amplitude and radial dependence of hypothesized inner core anisotropy are not well known. Apart from previously observed complexity in geometry, some recent results suggest changes in anisotropic properties in the regions of the inner core close to the planetary center. However, inadequate spatial sampling of the central inner core by PKP waves in all directions makes further advances on this topic very difficult. One of the reasons for this incomplete sampling lies in the fact that, in order to pass through the central regions of the inner core, PKP waves must be nearly antipodal. With the spatial distribution of large earthquakes and current configuration of seismographic stations worldwide, this is difficult to achieve, except for paths nearly parallel to the equatorial plane. Even if a large earthquake occurs at extreme latitudes, say at 50 degrees, although possible to find antipodally-positioned locations on the globe, such geometries could not produce angles between the PKP leg and the Earth's rotation axis (ksi) smaller than 35 degrees. This makes interpretation of anisotropic properties near the planet's center, at a minimum, very challenging. We proposed to study P’P’ waves to help achieving new spatial sampling of the inner core.

P’P’ and precursors to P’P’ at epicentral distances of about 50º-70º were observed and reported first in the 1960’s as small-amplitude arrivals on seismograms [*Gutenberg*, 1960]. Most prominent of P’P’ precursors were explained by waves generated by earthquakes or explosions that did not reach the Earth's surface but were reflected from the underside of first order velocity discontinuities at 410 and 660 km in the upper mantle [*Adams*, 1968; *Engdahl and Flinn*, 1969; *Whitcomb and Anderson*, 1970; *Richards*, 1972]. Since the time of these pioneering studies, numerous examples of precursors to P’P’ have been reported [e.g. *Davis et al*., 1989], indicating that structure of the upper mantle was not uniformly smooth.

A scattering hypothesis [e.g. *Cleary and Haddon*, 1972*; Haddon et al*., 1977; *Cleary*, 1981] for the origin of the P’P’ precursors, however, soon cast considerable doubt on the hypothesis of underside reflection from radial discontinuities. Forward scattering from small-scale (10-100 km) heterogeneities in the lowermost and uppermost mantle could explain the combined behavior of the frequency content, angle of approach, and complexity of the P’P’ precursors, accounting for a majority of the observed P’P’ and PKP precursor observations. P’P’ precursors whose arrival times corresponded to possible reflections from radial discontinuities at shallower depths in the mantle (<220 km) were hence dismissed as the effects of either scattering in the lowermost mantle or distributed heterogeneity in the uppermost mantle [*Haddon et al*., 1977].

Observation of Near-Podal P’P’ Precursors

A common characteristic of early observations of P’P’ and their precursors was that they were mostly assembled at epicentral distances of about 50°-70, which can be explained by the fact that a maximum amplitude of PKP waves due to a triplication occurs between 145° and 155° (Figure 1b). Unlike the majority of these earlier observations of P’P’ precursors, we report unprecedented observations at near-podal epicentral distances (<10°) of highly energetic P’P’ precursor arrivals (Figure 2). This is a result of a systematic and thorough search for podal P’P’ arrivals from waveforms available through the IRIS data center, for both individual and array stations [*Tkalčić and Flanagan*, 2004].

An example of P'P' precursor observations at the short-period ILAR array in Alaska is illustrated in Figure 2. Vertical components for two band-pass filters: a) 0.2-0.7 Hz and b) 1.0-1.5 Hz are shown. The event was located in southern Alaska, about 7 degrees away from ILAR array (Figure 1c). At 0.2-0.7 Hz, the main P'P' and the precursor arrivals of energy are visible at all ILAR stations. The main P'P' phase arrives within ±1 second as predicted by ak135 model [*Kennett et al.*, 1995] and even with up to 2 second error due to possible event mislocation, there are no other seismic phases arriving within this time window that could cause misinterpretation. At 1.0-1.5 Hz, the energy of the main phase is below noise level, but energetic signals of the precursors persist. The precursor energy is visible up to 3Hz, which motivates us to take a closer look at properties such as scattering and attenuation along a P'P' ray-path.

Interpretation of Near-Podal P'P' Precursors

Scattering of P'P' waves can occur anywhere along the ray path beneath the receiver, core-mantle boundary, inner-core boundary, or antipodal bounce point area. If P'P' waves were forward-scattered, simple travel time calculations reveal that all forward scattering would arrive as energy following P'P' rather than as a precursor. This is a distinguishing property of near-podal geometry and is true regardless of the location or distribution of scatterers in the mantle. For some strong velocity anomalies concentrated near the receiver, it is possible to create some P'P' precursors, but they would arrive with very different slowness than the main P'P' phase. Our slowness analysis shows that both the P'P' waves and the precursors have similar slowness (Figure 3).

It is highly unlikely for our observations that a specific near-source geometry-related effect, such as a dipping slab, where high-velocity in the slab would propagate P energy faster along the slab, could cause multi-pathing. First, mechanisms with a P-wave energy radiation pattern favorable to produce a podal P'P' phase are thrust faulting source mechanisms, where one lobe with maximum P-wave energy extends vertically downward from the source region. The seismic energy that is released in the direction of the slab is thus much smaller than the main P'P' energy (unless the slab itself is not vertical). Even if this were the case for observations at ILAR, which were recorded in Alaska above the subducting Pacific plate, it is impossible to acquire as much as 55-60 seconds of advance time. Furthermore, we also observe similar P'P' precursors on another, independent set of broadband recordings, for an Afghanistan-Tajikistan border earthquake (1999/11/08 16:45:44.3; 36.475°, 71.230°), recorded at the Tien Shan Continental Dynamics (GHENGIS) and Kyrgyz Seismic Telemetry (KNET) regional seismic networks (Figures 4a,4b). These precursors had advance times similar to that observed at ILAR, also inconsistent with forward scattering from any dipping structure associated with the intermediate depth earthquakes in this region. Further evidence against forward scattering or multipathing near the receiver is given by an azimuth slowness analysis of data from ILAR array [*Koper*, 2005], which found strikingly similar slowness and back-azimuth for both the precursor and main P'P' phase, that agree well with the location of the earthquake (Figure 3). Despite the fact that ILAR is a small aperture array and cannot provide high-resolution determination of slowness in an absolute sense, our results demonstrate that the relative directions of the incoming energy for both phases are similar and hence more consistent with back scattering. Moreover, a P'P' ray-path at near-podal epicentral distances could be thought of in terms of two antipodal PKP legs. If forward scattering were responsible for the precursors, they would also be observed for antipodal PKP ray-paths. Although there are many antipodally-observed PKP waveforms with a high quality of signal to noise available, precursors to antipodal PKP waves have never been reported.

Results of our azimuth slowness analyses are also inconsistent with precursor origin from scattering near the core-mantle boundary. It has been suggested that various scattered phases of PKP as well as PK(KKP) or PKK(KP) (where parentheses indicated scattered part of the signal) might account for precursors of PKKKP (double reflection from the inner side of the core mantle boundary) and P'P' waves. These could be an alternate explanation to underside reflections from 410- and 660-km discontinuities at epicentral distances equal and longer than 30° [*Cleary*, 1981; *Vinnik*, 1974; *Muirhead*, 1985]. Even if these calculations were extrapolated to shorter distances, forward-scattered PKP branches would arrive with very different slowness and PKKKP waves would arrive earlier than our observed precursors. PKKKP-BC phase could be recorded on seismograms at about the same time when the precursors to P'P' are observed (see Figure 1b), but the BC branch of PKKKP has a very different slowness than the DF branch of P'P' at near-podal epicentral distances, and based on our observations of near-zero slowness at GHENGIS and KNET networks, we can also eliminate this possibility.

Therefore, we suggest that the observed P'P' precursors are back-scattered energy from reflectors in the upper mantle (see Figure 1d). Back-scattered energy at near-podal epicentral distance would have a higher frequency content than the main phase and virtually the same slowness, consistent with our analysis. Travel time calculations show that the earliest individual packet of energy at about 57 s preceding P'P' corresponds to an underside reflection from about 220 km depth, and the latest packet at about 30 seconds preceding P'P' corresponds to a reflection from a depth of 150 km. A 220-km discontinuity is not yet confirmed as a global property of Earth, however there are numerous sporadic observations beneath both continents and oceans worldwide [e.g. *Gu et al*., 2001]. There is also evidence for a reflector at 200 km depth beneath the northwest Pacific from precursors to PP waves [*Rost and Weber*, 2001]. The reflection points of the observed P'P' for all Alaskan earthquakes are in the Antarctic plate, north of Antarctica and far from mid-ocean ridges (Figure 1c), where precursors to P'P' at longer epicentral distances were reported by *Adams* [1971].

Because PKP waves have maximum amplitudes near 150º, it is not surprising that most observations of P'P' and their precursors associated with 410- and 660-km discontinuities are made near epicentral distances of 60º. An interesting factor to consider is the observability of reflections from upper mantle discontinuities having topography [e.g. *Flanagan and Shearer*, 1998]. Since 410- and 660-km discontinuities have opposite Clapeyron slopes, they move in opposite directions when their positions are perturbed by lateral temperature variations. For example, a cold environment perturbs the 660-km discontinuity downwards, so a convex region of 660-km discontinuity acts like defocusing lens. We examined cross sections of shear velocity tomograms [*Ritsema et al*., 1999] in this region and found that indeed the 150-220 km depth zone is confined within a large cold domain in the upper mantle extending below 660 km. This, along with the fact that the corresponding PKP waves are far from their maximum amplitude at near-podal distance, might explain why there are no prominent observations of underside reflections from the 660-km discontinuity for near-podal P'P'.

The higher frequency content of the precursors to P'P' may be explained by a combination of the effects of higher attenuation in the uppermost mantle and the frequency dependence of backscattered energy from small-scale heterogeneities. The effects of upper mantle attenuation are relatively simple to model. Modeling the effects of the back-scattered radiation pattern of small-scale heterogeneities is necessarily more speculative. The largest effect on frequency content, however, will most likely be that of the exponential attenuation of amplitude with frequency due to intrinsic attenuation rather than the simple first and second order power law decrease in amplitude with frequency due to scattering by heterogeneities of varying scale length and shape. Hence, we first consider the effects of mantle attenuation on the backscattered energy.

The difference in the attenuation experienced by P'P' relative to the back-scattered precursors is simply given by the effect of the travel time accumulated by the additional two legs of the main P'P' phase ray-path in the attenuating uppermost 150-220 km of the mantle. In Figure 5 we plot predictions of precursor spectra based on the spectra of the main phase assuming that Q is constant with frequency in the lithosphere (Figure 5a) according to $A_{precursor} = A_{main} \cdot e^{\frac{-\pi f \Delta t}{Q_{const}}}$, where Δt is the two way travel time through the antipodal lythosphere. The high-energy content of the precursor compared to the main arrivals can be explained by the difference in attenuation experienced by the additional two legs that the main PKPPKP phase spends in the antipodal lithosphere with a frequency-dependent Q in the upper mantle. In Figure 5b we assume a frequency dependent Q model, having a flat relaxation spectra below 0.1 Hz with increasing Q as the first power of frequency above 0.1 Hz according to *Choy and Cormier* [1986]. Q_{const} from the above formula now becomes Q(f). Our preferred Q model for the antipodal bounce point region from ILAR (oceanic upper mantle in the surrounding Antarctica) has a constant relaxation spectrum below 0.1 Hz, and Q increasing with the first power of frequency above 0.1 Hz. The frequency dependence agrees with that first proposed by *Gutenberg* [1958], who suggested a Q proportional to frequency to predict the observed amplitudes of high frequency P'P'P'.

To achieve a better fit to the lower frequency band of precursor energy, we investigated the effects of possible frequency dependent scattering. For Rayleigh scattering (scatterer scale lengths much smaller than wavelength), the radiation patterns of scattered particle velocity will contain a factor proportional to the square of frequency [*Sato and Fehler*, 1998]. For either thin lenses of heterogeneity, oriented perpendicular to an incident wavefront or for the integrated effect of connected small scale heterogeneity, we might expect this frequency dependence to be proportional to the first power of frequency. The combined effect of back scattering for the bottom and top boundary of partial melt lenses is $-R*v(t)+R*v(t+\Delta t)$, where v is velocity, R is reflection coefficient (negative for liquid over solid and positive for solid over liquid) and Δt is the two way travel time through thin liquid layer. We assumed the velocity in the solid to be equal to 10 km/s and velocity in the liquid to be equal to 4 km/s. We neglect transmission coefficients through the bottom of the thin layer, As the thin layer goes to zero thickness, the above expression can be approximated with –R*□t*dv/dt, and if we assume plane wave incidence, *dv/dt* equals to i*□*v, where □ is frequency. Assuming back-scattered radiation patterns proportional to the first power of frequency together with the effect of a frequency dependent *Q* model, we now achieve better fits to predicted precursor energy in the lower end (0.2 to 0.5 Hz) of the band in which signal to noise ratios are high for the main P’P’ phase (Figure 5c).

Discussion

We interpret our best fit to the frequency content and slowness of near-podal P’P’ precursor energy as backscattering from horizontally connected small-scale heterogeneity concentrated in the uppermost 150-220 km of the mantle. Possible candidate scatterers include compositional blobs of variable size and elastic impedance or lenses of partial melt. Compositional heterogeneities may be eclogitic slab fragments [e.g. *Allegre and Turcotte*, 1986; Anderson, 2005]. The impedance contrasts of the heterogeneities may also be associated with a rheologic change from dislocation creep to diffusion creep, which has been proposed as a mechanism to account for a transition from an anisotropic uppermost mantle to an isotropic lower mantle [*Karato*, 1992]. Partial melt lenses are more effective than either compositional or solid-solid phase changes in accounting for the large impedance contrasts needed to account for the amplitude of the observed P’P’ precursors at ILAR. Our best observations of P’P’ precursors back-scattered from this depth range at ILAR occur beneath oceanic regions, far from mid-ocean ridges. Little or no partial melt, however, has ever been postulated in the upper mantle as deep as 150-220 km, far from mid-ocean ridges. Compared to P’P’ precursors observed at ILAR, precursors observed from P’P’ in the Afganistan-Tajikistan Border region have relatively lower frequency content, perhaps related to an antipodal bounce point near the Pacific mid-ocean ridge. Important future observations include an assessment of regional variations in the frequency content of P’P’ precursors, especially whether similar back-scattering is observed beneath continental regions. Perhaps the mechanism producing the backscattering from a diffuse 150-220 km deep zone, a possible plate decoupling zone beneath oceanic regions is identical to the mechanism producing occasional observations of a Lehmann discontinuity near 220 km depth beneath continental regions.

The near-podal PKPPKPdf waves with various geometries worldwide, observed so far, are very encouraging. Figures 6 and 7 illustrate examples of near-podal PKPPKPdf observation, recorded by station MINA for a Nevada Test Site explosion and the Kyrgyz Seismic Telemetry Network for an Afganistan-Tajikistan border earthquake, respectively. In addition, Table 1 lists the events in Alaska for which P’P’ and their precursors were observed. Preliminary results from analyzing near-podal P’P’df travel times suggest that the central part of the inner core is not fast in the direction parallel to Earth's axis, which contradicts presently hypothesized anisotropy models. Painstakingly collected data points from near-podal P’P’df travel times will thus have very important implications for our understanding of the anisotropy and other properties of the deep inner core.

Exit Plan

In our opinion, we achieved a significant breakthrough in an attempt to better understand Earth's structure. We reported the discovery of hitherto unobserved near-podal P'P' waves (at epicentral distance less than 10º) and very prominent precursors preceding the main energy by as much as 60 seconds. Based on the timing and frequency content of these precursors we interpreted them as a back-scattered energy from horizontally connected small-scale heterogeneity in the upper mantle, in a zone between 150 and 220 km depth beneath Earth's surface. Possible candidate scatterers include compositional blobs of variable size such as eclogitic slab fragments or lenses of partial melt. While the existence of podal P'P' was theoretically predicted (although until now never observed), the existence of P'P' precursors is unexpected and intriguing. On the one hand, the podal P'P'phases themselves will provide new geometries with which to probe the deepest parts of the inner core, and on the other hand the high frequency precursors illuminate the scattering properties of the upper 200 km of Earth's mantle in a unique manner. These results should be of interest to a wide range of Earth scientists including seismologists involved in upper mantle structure, mineral physicists and mantle convection modelers who have hypothesized various mantle mixing models regarding slab fragments.

Summary

This work was very well received in the seismological community beginning with an invited talk at the 2004 Fall AGU (American Geophysical Union) meeting and poster presentations at the 2005 SSA (Seismological Society of America), 2005 IRIS (Incorporated Institutions in Seismology), and 2005 Fall AGU meetings. In addition, the PI Dr. Hrvoje Tkalcic was invited to give several one hour colloquia at a number of universities throughout 2005 including: Caltech, UC Berkeley, UC Santa Cruz, and University of Nevada Reno. Four meeting abstracts have been published and one manuscript has been accepted and it is currently in press for Geophysical Research Letters. Science magazine expressed their interest in publishing either Editor's Choice or News and Views type of report on these findings; the PI will keep the LDRD office informed. All of these activities have provided the PI's with an opportunity to showcase the high quality and diversity of seismological research performed at LLNL, and the PI's are grateful to the LDRD office for funding this work.

Figure and Table Captions:

Table 1. Table of selected events with prominent P'P' precursor observations, describing their locations and origin times, as well as the locations of the reflections points at the antipode. All data are available through the IRIS acquisition system

Figure 1. (a) Ray-path of podal P'P'df waves connecting the source (star) with the receiver (triangle). (b) Theoretical travel time curves of P'P' from sources at 0 and 500 km depth using ak135 [*Kennett et al.*, 1995] are shown by solid and dashed lines, respectively. The P'P'df branch corresponds to the waves bottoming in the inner core. PKKKP waves could be observed in the same epicentral distance range preceding P'P'df waves with significantly different slowness. (c) Surface projections of ray-paths from the events in Alaska (stars) for which we observe P'P' precursors on ILAR array (triangle). Stars in the southern hemisphere are bounce points near the antipode; circles are surface projections of the corresponding bottoming points in the inner core (one at source and another at receiver side). (d) Schematic representation of the reflection of P'P' waves in the antipodal mantle. Back scattering originates in a zone between 150 and 220 km in the upper mantle.

Figure 2. Vertical component records from ILAR array are shown for two bandpass filters: (a) 0.2-0.7 Hz and (b) 1.0-1.5 Hz. This earthquake (1999/07/28 07:32:44.6 lat=59.005°, lon=-155.099°) was located in the southern Alaska, about 7° southwest of ILAR array. Both the main P'P' phase and precursors are visible at lower frequencies. Precursors to P'P' are characterized by several distinct arrivals between approximately 57 and 30 s preceding P'P'. At higher frequencies, the main P'P' phase is below the noise level and not visible.

Figure 3. Horizontal components of optimal slowness vector (sx,sy) for: A) main P'P' phase and B) precursors to P'P' at ILAR. Peak amplitude as a function of slowness for beams formed from P'P' and precursor segments of the seismograms are shown by the star. The resulting back azimuths shown above are 238° and 239° for the main P'P' and precursors, respectively.

Figure 4a. Main P'P' phase observations for Afganistan-Tajikistan Border event on vertical broadband components of Tien Shan Continental Dynamics (GHENGIS) and Kyrgyz Seismic Telemetry (KNET) networks. The records are filtered between 0.15 and 0.75 Hz. Vertical line shows a theoretical P'P' arrival time from ak135 model. Total duration shown for each record is 200 seconds (tick marks are at each 10 seconds).

Figure 4b. Precursors to P'P' for Afganistan-Tajikistan Border event on vertical broadband components of Tien Shan Continental Dynamics (GHENGIS) and Kyrgyz

Seismic Telemetry (KNET) networks. The records are filtered between 0.5 and 1.5 Hz. Vertical line shows a theoretical P'P' arrival time from ak135 model. Total duration shown for each record is 200 seconds (tick marks are at each 10 seconds). Note that the main phase is not visible at these frequencies and that the timing and frequency content of the precursors look very similar to the observed ones at ILAR network (compare to Figure 2 in the paper).

Figure 5. Amplitude spectra for the observed main P'P' phase (thick black line), P'P' precursor (thick gray line) and noise preceding the precursors (dashed gray line). The spectrum of the main phase was used to calculate predictions of precursor spectrum (thin black lines). (a) Only the frequency effect of Q without the frequency dependence of scattering was taken into account. Q is assumed to be constant in the antipodal lithosphere. The used values for Q are shown above the theoretical curves. (b) Same as (a) but Q is constant for frequencies below and increases with the first power of frequency above a given corner frequency. For Q=200, frequency corners of 0.1 ($\square_1$) and 0.05 Hz ($\square_2$) were used. (c) Q varies with frequency in the same way as in (b), but with frequency dependence proportional to the first power of frequency in order to account for integrated effect of connected thin lenses of partial melt.

Figure 6. An observation of P'P' at station MINA, Nevada, after a zero-phase stack of the waveforms produced by two nuclear explosions. The waveforms are shown both in time domain (seismograms) and in frequency domain (spectrogram). The ray-path associated with this observation samples Earth very close to its center (about 50 km in high-frequency approximation). The resulting travel time residual is not anomalous with respect to the reference 1D model of Earth, arguing for non-anisotropic center of Earth in the direction described by this ray-path (about 50º with respect to Earth's rotation axis).

Figure 7. An observation of main near-podal P'P' phase at Hindu Kush region, underlining the predicted phase offset by ak135 model (red line) and PKKKP offset by blue line. The slowness of the observed phase argues against PKKKP and for P'P' observations.

References

Adams, R.D.,, Early reflections of P'P' as an indication of upper mantle structure, *Bull. Seism. Soc. Am.*, 58, 1933-1947, 1968.

Adams, R.D., Reflections from discontinuities beneath Antarctica, *Bull. Seism. Soc. Am.*, 61, 1441-1451, 1971.

Allegre, C.J., and D.L. Turcotte, Implications of a two-component marble-cake mantle, *Nature*, 323, 123-127, 1986.

Anderson, D.L., Speculations on the nature and cause of mantle heterogeneity, submitted to *Phys. Earth Planet. Inter*, 2005.

Choy, G.L. and V.F. Cormier, Direct measurement of the mantle attenuation operato from broadband P and S waveforms, *J. Geophys. Res*., 91, 7326-7342, 1986.

Cleary, J.R., and R.A.W. Haddon, Seismic wave scattering near the core-mantle boundary: A new interpretation of precursors to PKP, *Nature*, 240, 549-551, 1972.

Cleary, J.R., Seismic wave scattering on underside reflection at the core-mantle boundary, *Phys. Earth Planet. Inter*., 26, 266-267, 1981.

Davis, J.P., R. Kind, and I.S. Sacks, Precursors to P'P' re-examined using broadband data, *Geophys. J. Int*., 99, 595-604, 1989.

Engdahl, E.R., and E.A. Flinn, Seismic waves reflected from discontinuities within the Earth's upper mantle, *Science*, 163, 177-179, 1969.

Flanagan, M.P. and P.M. Shearer, Global mapping of topography on transition zone velocity discontinuities by stacking SS precursors, *J. Geophys. Res*., 103, 2673-2692, 1998.

Gu, Y.J., A.M. Dziewonski, and G. Ekström, Preferential detection of the Lehmann discontinuity beneath continents, *Geophys. Res. Lett.*, 28, 4655-4658, 2001.

Gutenberg, B., Waves reflected at the "surface" of the Earth: P'P'P'P'*, Bull. Seismol. Soc. Am.*, 50, 71-79, 1960.

Gutenberg, B., Attenuation of seismic waves in the Earth's mantle, *Bull. Seism. Soc. Am.*, 48, 269-282, 1958.

Haddon, R.A.W., E.S. Husebye, and D.W. King, Origins of precursors to P'P', *Phys. Earth Planet. Int*., 14, 41-70, 1977.

Karato, S.-I, On the Lehmann discontinuity, *Geophys. Res. Lett.*, 19, 2255-2258, 1992.

Kennett, B.L.N., E.R. Engdahl, and R. Bulland, Constraints on seismic velocities in the Earth from traveltimes, *Geophys. J. Int*., 122, 108-124, 1995.

Koper, K., Generic Array Processing Code, available at http://www.eas.slu.edu/People/KKoper/Free/index.html.

Muirhead, K., Comments on "Reflection properties of phase transition and compositional change models of the 670-km discontinuity" by A.C. Lees, M.S.T. Bukowinski, and R. Jeanloz, *J. Geophys. Res*., 90, 2057-2059, 1985.

Richards, P.G., Seismic waves reflected from velocity gradient anomalies within the Earth's upper mantle, *Zeitschrift für Geophysik*, 38, 517-527, 1972.

Rost, S., and M. Weber, A reflector at 200 km depth beneath the northwest Pacific, *Geophys. J. Int*., 147, 12-28, 2001.

Ritsema, J., H.J. van Heijst, and J.H. Woodhouse, Complex shear wave velocity structure imaged beneath Africa and Iceland, *Science*, 289, 1925-1928, 1999.

Sato, H., and M. Fehler, *Seismic Wave Propagation and Scattering in a Heterogeneous Earth*, Springer, 1998.

Tkalčić, H., and P.M. Flanagan, Structure of the deep inner core from antipodal PKPPKP waves, *Eos Trans. AGU* 85(47), Fall Meet. Suppl., Abstract T54A-06, 2004.

Tkalčić, H., P.M. Flanagan and V.F. Cormier, Observation of near-podal P'P' precursors: Evidence for back scattering from the 150-220 km zone in the Earth's upper mantle, *Geophys. Res. Lett*., in press.

Vinnik, L.P., Scattering of longitudinal waves in the Earth, *Fizika Zemli*, 11, 37-56, 1974.

Whitcomb, J.H., and D.L. Anderson, Reflection of P'P' seismic waves from discontinuities in the mantle, *J. Geophys. Res*., 75, 5713-5728, 1970.

Acknowledgments:

We are most grateful to the Laboratory Directed Research and Development Program (LDRD) office of LLNL for granting funds for this project; IRIS data center for high quality of the acquisition system; K. Koper for making his software available; J. Ritsema and E. Garnero for comments and B. Urhammer, P. Richards, A. Rodgers, L. Hutchings, D. Harris and W. Walter for discussions. This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Event time	Event depth and region	Event lat.	Event lon.	Reflection point lat.	Reflection point lon.
2000/05/19 20:34:27.4	80.0km; Alaska	59.178	-153.190	-62.010	29.680
2001/01/25 05:29:38.4	95.8; Alaska	60.312	-152.680	-62.580	30.000
2001/07/28 07:32:44.6	133.6; Alaska	59.005	-155.009	-61.960	28.630
2003/02/27 15:35:30.7	202.0; Alaska	58.710	-156.870	-61.840	27.650
1999/11/08 16:45:44.3	228km; Afgan.Tajik.	36.475	71.230	-35.06	-107.73

Table 1

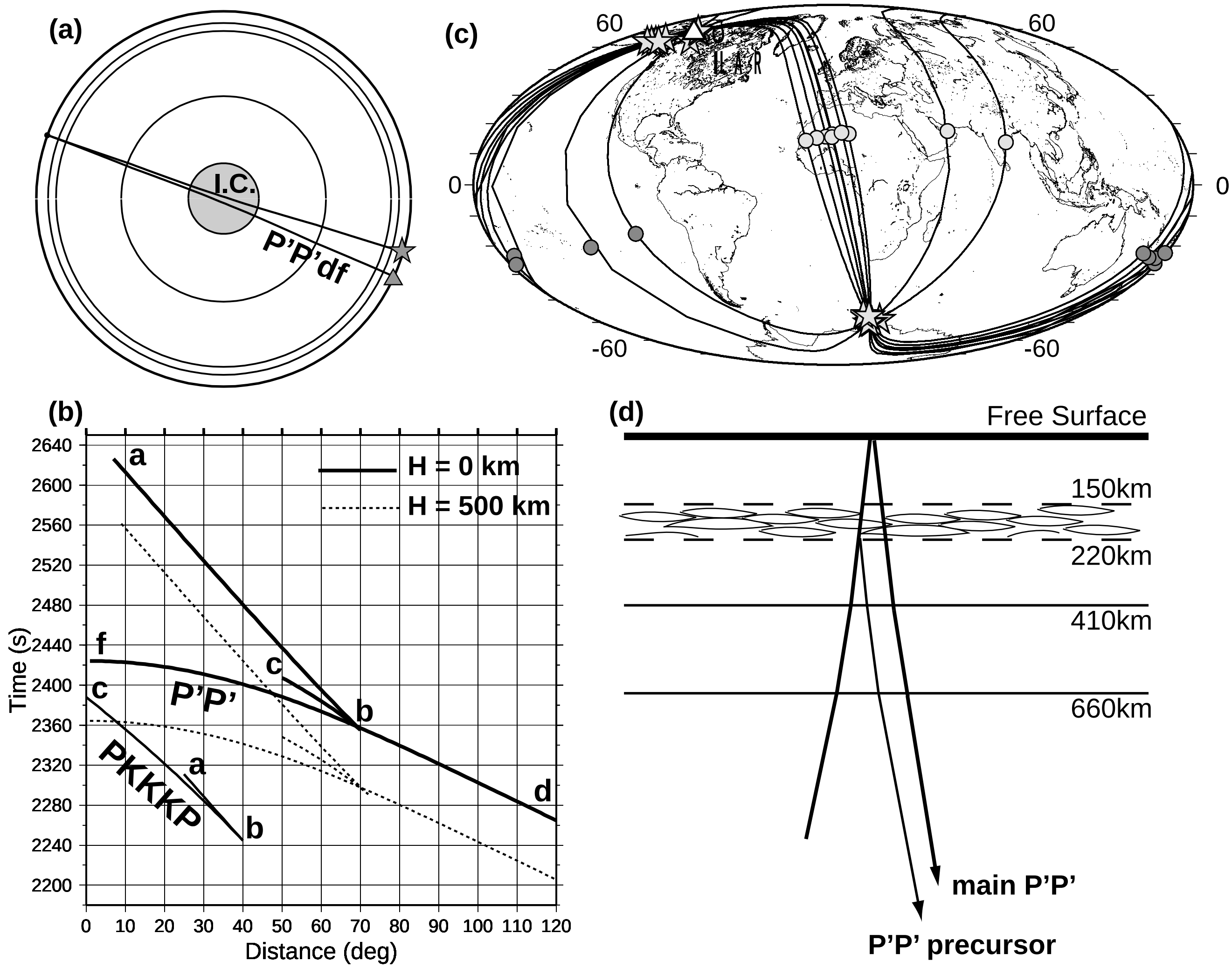

(a)
I.C.
P'P'df
(c)
60
60
0
0
-60
-60
(b)
H = 0 km
H = 500 km
a
f
c
P'P'
c
b
a
PKKKP
b
d
Time (s)
Distance (deg)
2640
2600
2560
2520
2480
2440
2400
2360
2320
2280
2240
2200
0 10 20 30 40 50 60 70 80 90 100 110 120
(d)
Free Surface
150km
220km
410km
660km
main P'P'
P'P' precursor

Figure 1

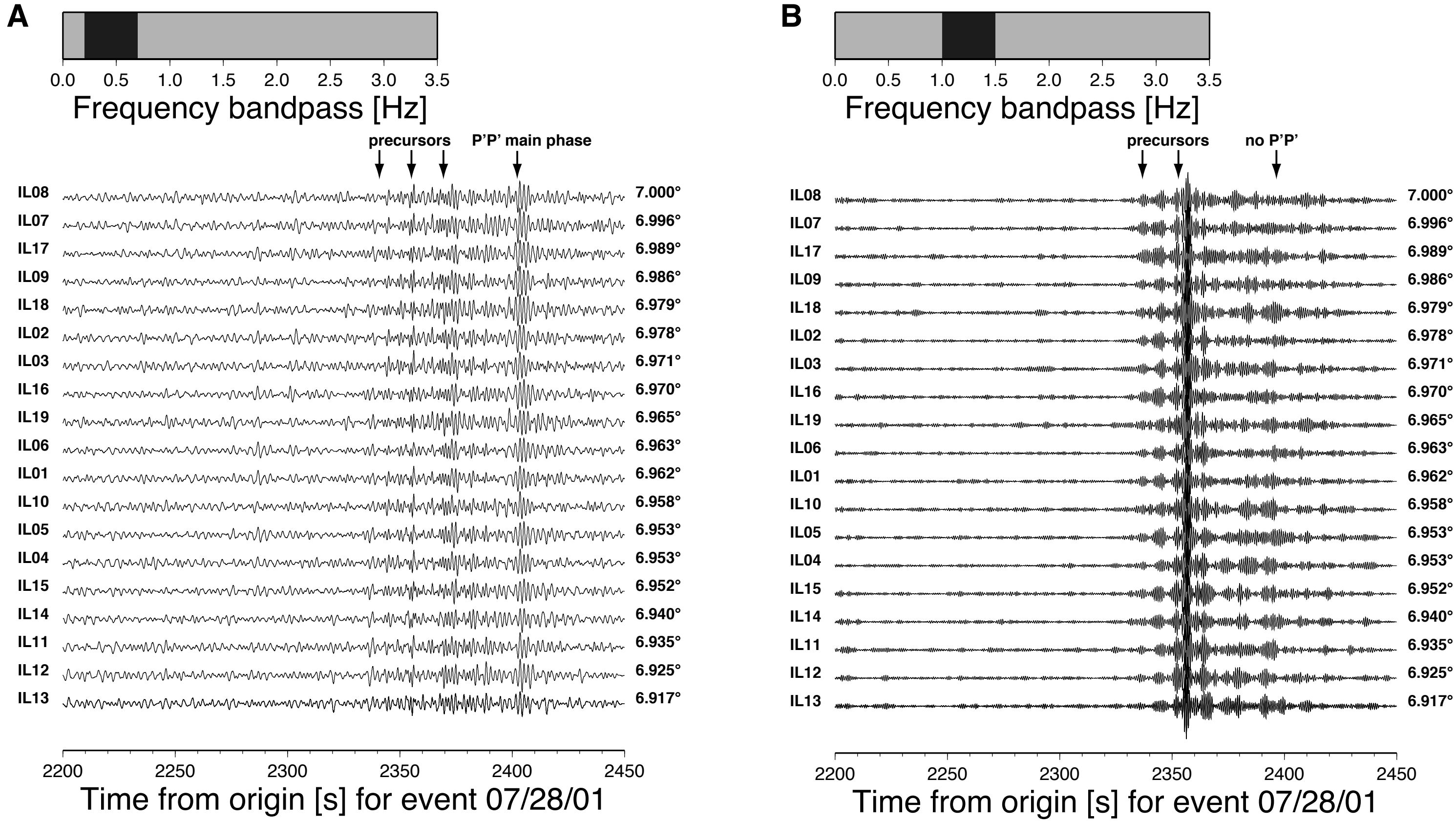

A
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
Frequency bandpass [Hz]
precursors
P'P' main phase
IL08 7.000°
IL07 6.996°
IL17 6.989°
IL09 6.986°
IL18 6.979°
IL02 6.978°
IL03 6.971°
IL16 6.970°
IL19 6.965°
IL06 6.963°
IL01 6.962°
IL10 6.958°
IL05 6.953°
IL04 6.953°
IL15 6.952°
IL14 6.940°
IL11 6.935°
IL12 6.925°
IL13 6.917°
2200 2250 2300 2350 2400 2450
Time from origin [s] for event 07/28/01
B
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
Frequency bandpass [Hz]
precursors
no P'P'
IL08 7.000°
IL07 6.996°
IL17 6.989°
IL09 6.986°
IL18 6.979°
IL02 6.978°
IL03 6.971°
IL16 6.970°
IL19 6.965°
IL06 6.963°
IL01 6.962°
IL10 6.958°
IL05 6.953°
IL04 6.953°
IL15 6.952°
IL14 6.940°
IL11 6.935°
IL12 6.925°
IL13 6.917°
2200 2250 2300 2350 2400 2450
Time from origin [s] for event 07/28/01

Figure 2

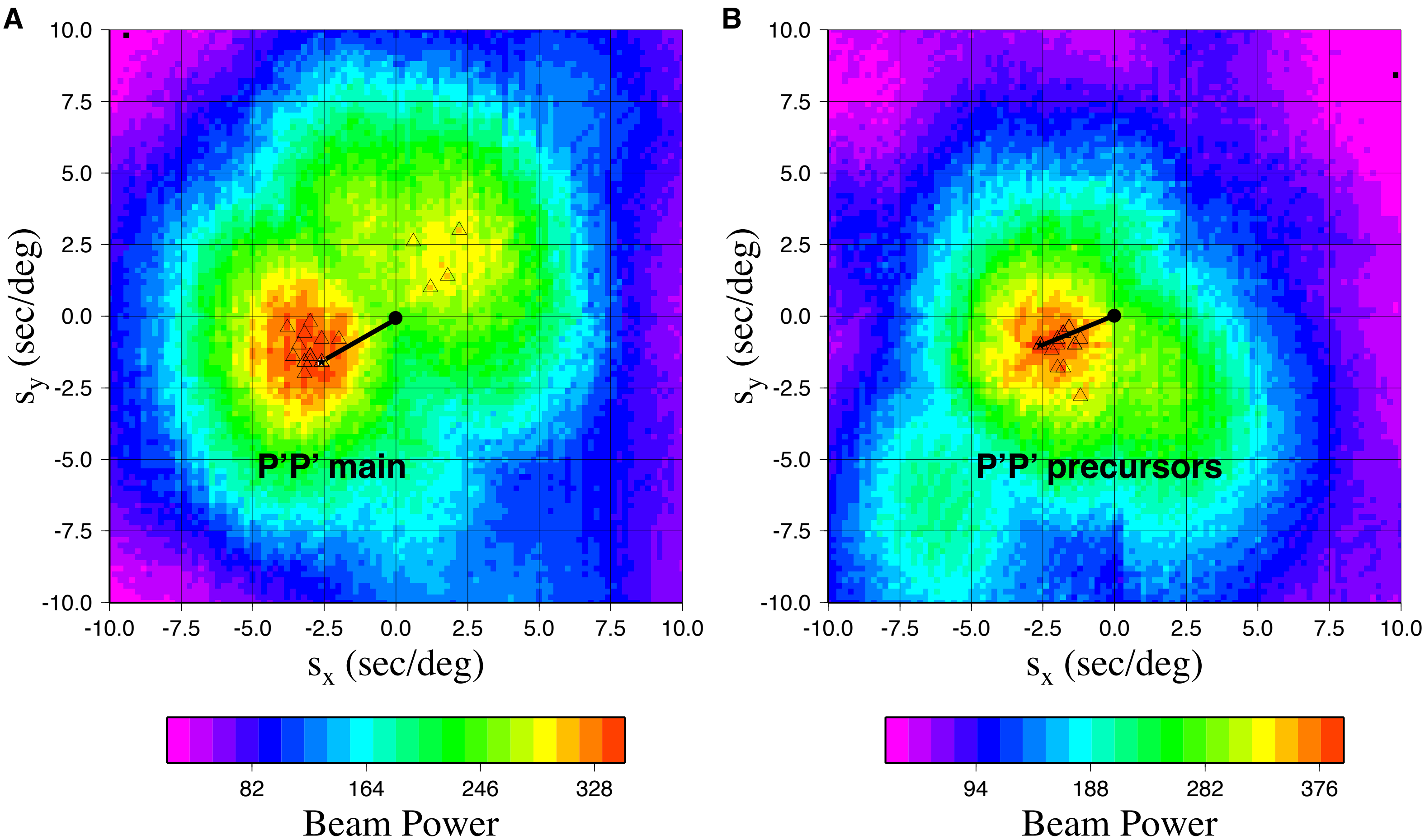

A
B
P’P’ main
P’P’ precursors
s_y (sec/deg)
s_x (sec/deg)
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
-7.5
-10.0
82
164
246
328
94
188
282
376
Beam Power

Figure 3

Afganistan-Tajikistan Border Event 1999/11/08 Mw=6.5

Figure 4a

Afganistan-Tajikistan Border Event 1999/11/08 Mw=6.5

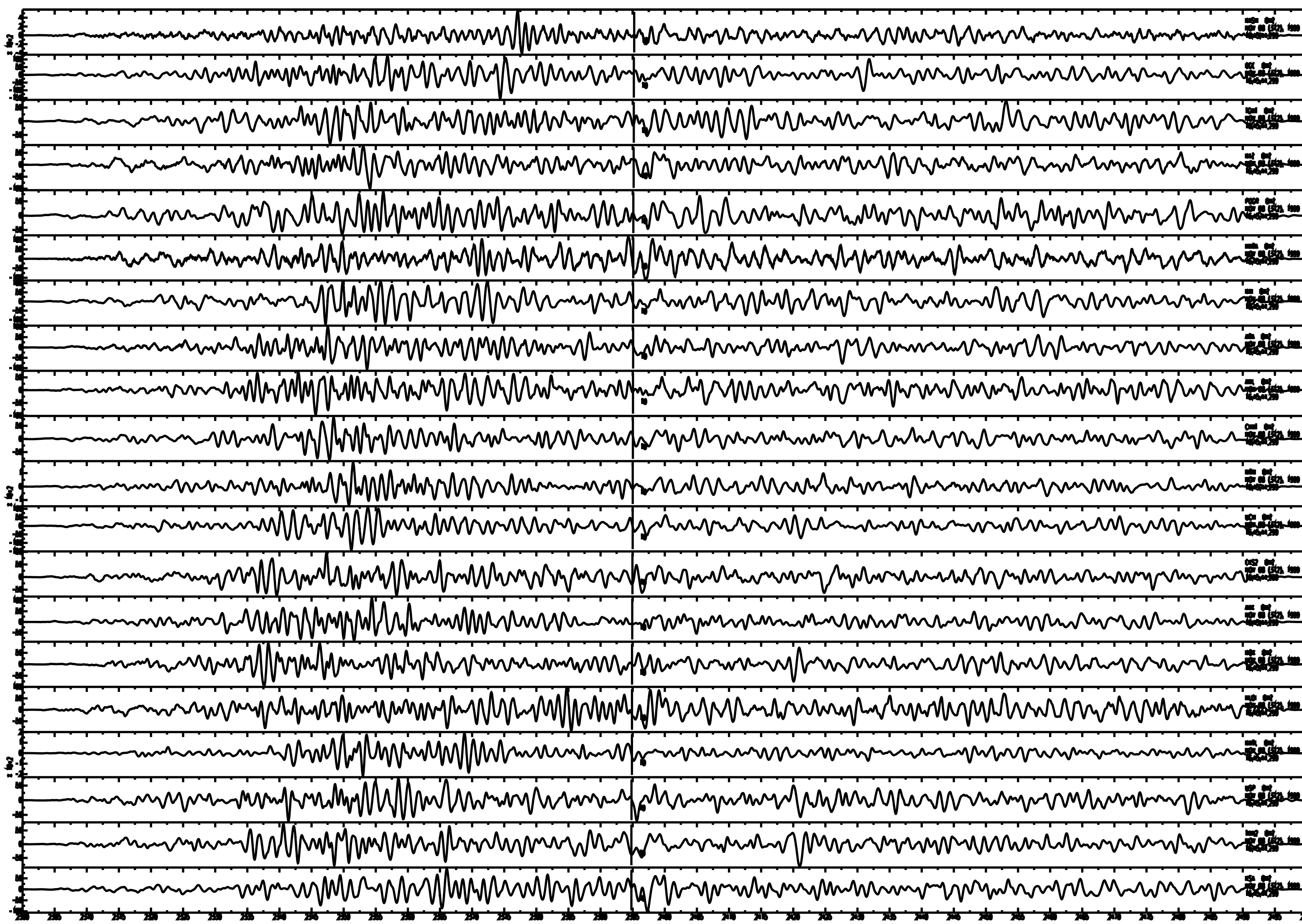


Figure 4b

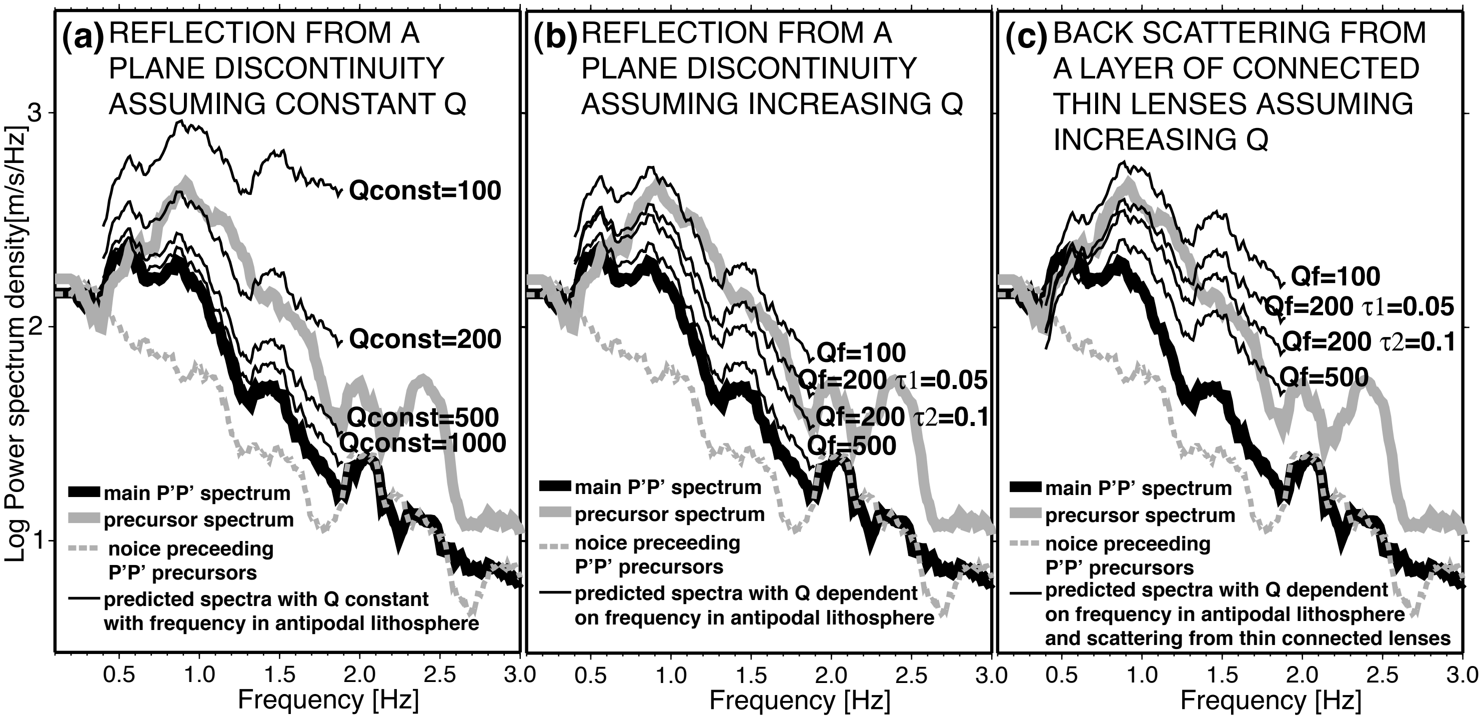
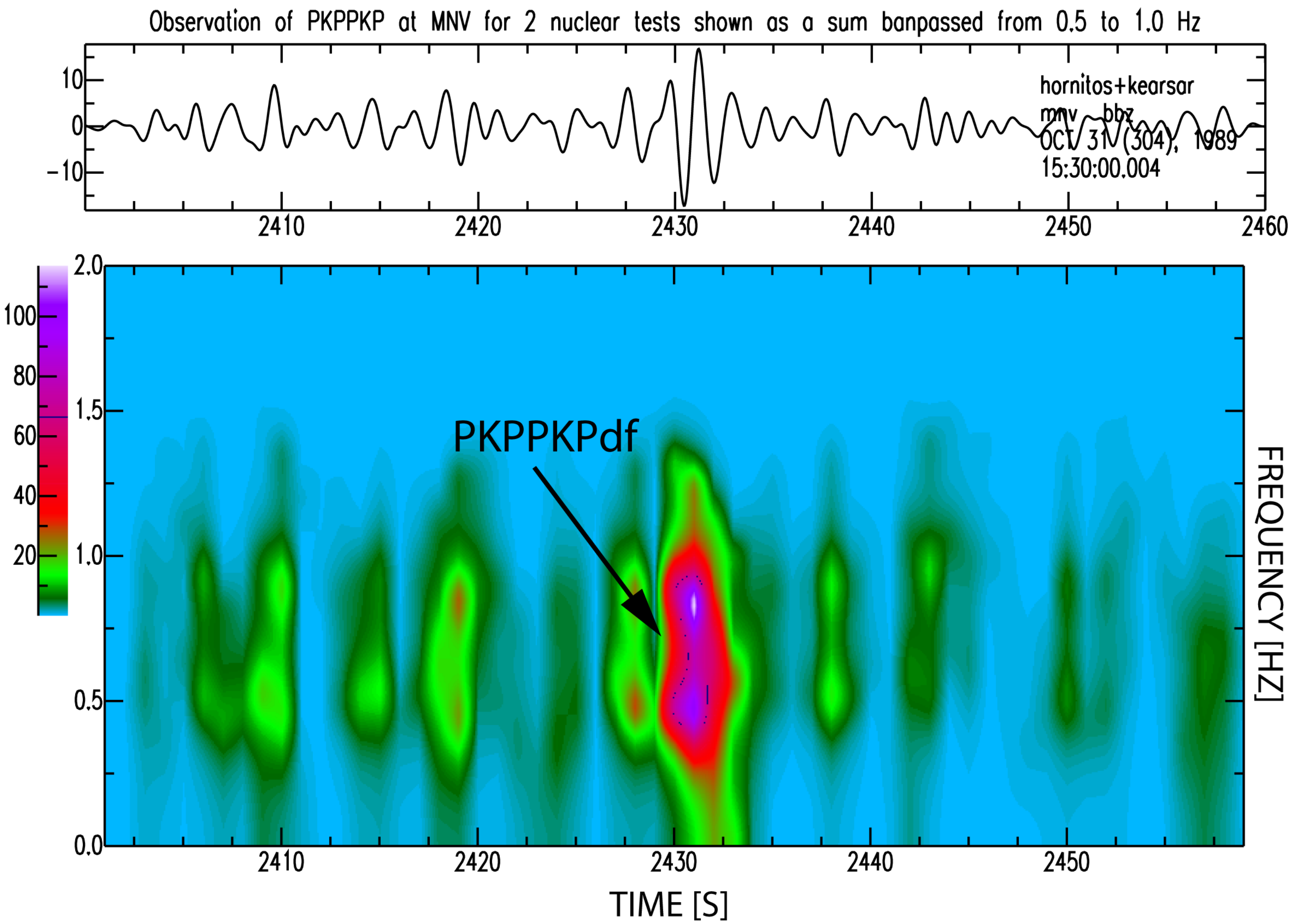

(a) REFLECTION FROM A PLANE DISCONTINUITY ASSUMING CONSTANT Q
(b) REFLECTION FROM A PLANE DISCONTINUITY ASSUMING INCREASING Q
(c) BACK SCATTERING FROM A LAYER OF CONNECTED THIN LENSES ASSUMING INCREASING Q
Log Power spectrum density[m/s/Hz]
3
2
1
Qconst=100
Qconst=200
Qconst=500
Qconst=1000
Qf=100
Qf=200 τ1=0.05
Qf=200 τ2=0.1
Qf=500
main P'P' spectrum
precursor spectrum
noice preceeding P'P' precursors
predicted spectra with Q constant with frequency in antipodal lithosphere
predicted spectra with Q dependent on frequency in antipodal lithosphere
predicted spectra with Q dependent on frequency in antipodal lithosphere and scattering from thin connected lenses
0.5
1.0
1.5
2.0
2.5
3.0
Frequency [Hz]

Figure 5



Observation of PKPPKP at MNV for 2 nuclear tests shown as a sum banpassed from 0.5 to 1.0 Hz
hornitos+kearsar
mnv bbz
OCT 31 (304), 1989
15:30:00.004
PKPPKPdf
FREQUENCY [HZ]
TIME [S]

Figure 6

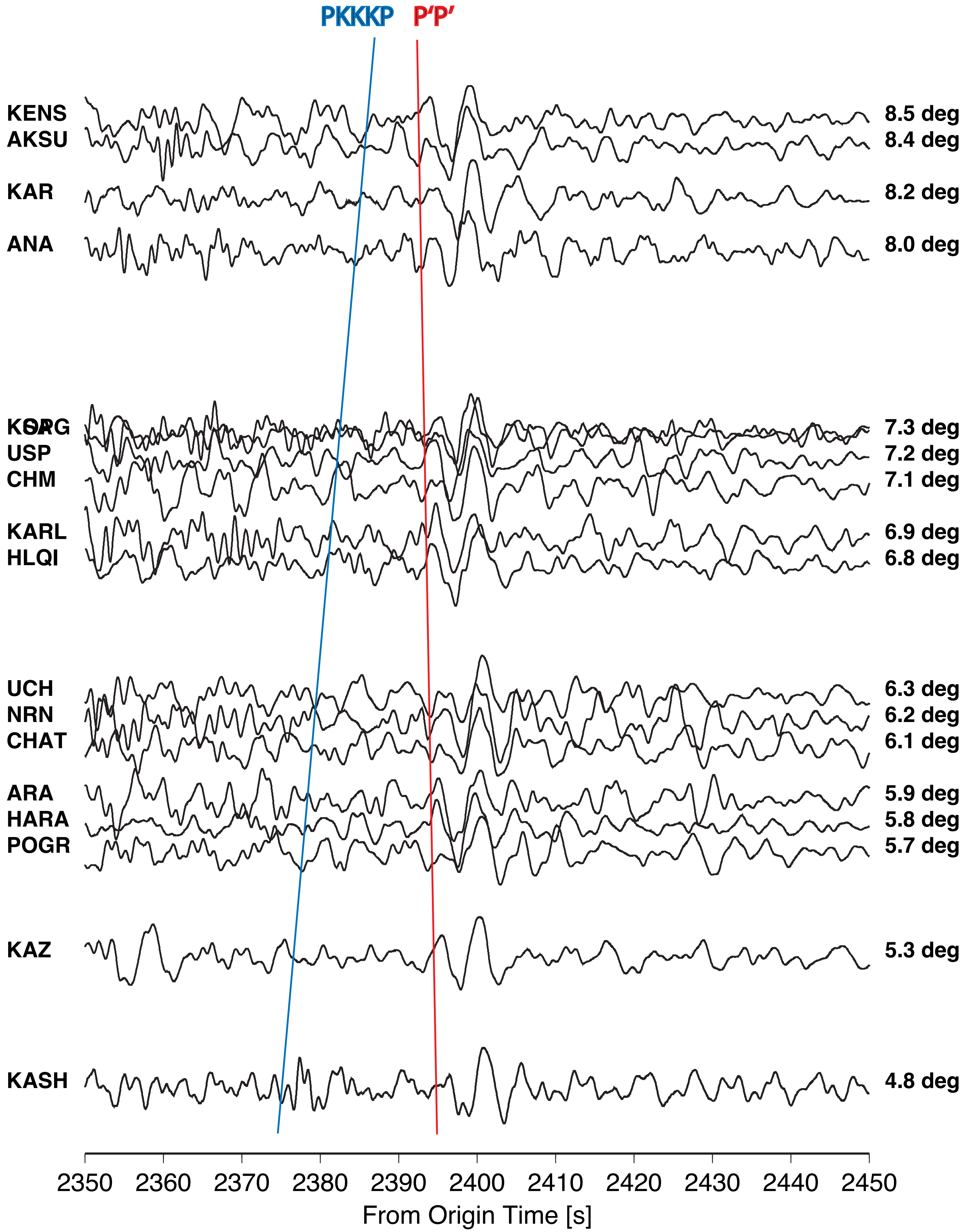

PKKKP
P′P′
KENS
AKSU
KAR
ANA
KSAR
KSPG
USP
CHM
KARL
HLQI
UCH
NRN
CHAT
ARA
HARA
POGR
KAZ
KASH
8.5 deg
8.4 deg
8.2 deg
8.0 deg
7.3 deg
7.2 deg
7.1 deg
6.9 deg
6.8 deg
6.3 deg
6.2 deg
6.1 deg
5.9 deg
5.8 deg
5.7 deg
5.3 deg
4.8 deg
2350
2360
2370
2380
2390
2400
2410
2420
2430
2440
2450
From Origin Time [s]

Figure 7